

On the origin of short GRBs with Extended Emission and long GRBs without associated SN

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ABSTRACT

The Burst and Transient Source Experiment (BATSE) classifies cosmological gamma-ray bursts (GRBs) into short (less than 2 s) and long (over 2 s) events, commonly attributed to mergers of compact objects and, respectively, peculiar core-collapse supernovae. This standard classification has recently been challenged by the *Swift* discovery of short GRBs showing Extended Emission (SGRBEE) and nearby long GRBs without an accompanying supernova (LGRBN). Both show an initial hard pulse, characteristic of SGRBs, followed by a long duration soft tail. We here consider the spectral peak energy ($E_{p,i}$)-radiated energy (E_{iso}) correlation and the redshift distributions to probe the astronomical and physical origin of these different classes of GRBs. We consider *Swift* events of 15 SGRBs, 7 SGRBEEs, 3 LGRBNs and 230 LGRBs. The spectral-energy properties of the initial pulse of both SGRBEE and LGRBNs are found to coincide with those of SGRBs. A Monte Carlo simulation shows that the redshift distributions of SGRBs, SGRBEE and LGRBNs fall outside the distribution of LGRBs at 4.75σ , 4.67σ and 4.31σ , respectively. A distinct origin of SGRBEEs with respect to LGRBs is also supported by the elliptical host galaxies of the SGRBEE events 050509B and 050724. This combined evidence supports the hypothesis that SGRBEE and LGRBNs originate in mergers as SGRBs. Moreover, long/soft tail of SGRB and LGRBNs satisfy the same $E_{p,i} - E_{iso}$ Amati-correlation holding for normal LGRBs. This fact points to rapidly rotating black holes as a common long-lived inner engine produced by different astronomical progenitors (mergers and supernovae).

Key words: stars: black holes – gamma-ray bursts: general – stars: neutron

1. INTRODUCTION

The bimodal distribution in the Burst and Transient Source Experiment (BATSE) catalogue of cosmological gamma-ray bursts (GRB) reveals long GRBs (LGRB) commonly associated with core-collapse in massive stars (Woosley 1993) and short GRBs (SGRBs) commonly associated with mergers of compact objects, i.e., neutron stars with another neutron star (NS-NS, Eichler et al. (1989)) or a stellar mass black hole companion (NS-BH, Paczyński (1991)). The first is supported by three pieces of evidence: *i*) supernovae (SNe) accompanying a few nearby events (Hjorth & Bloom 2011); *ii*) detection of SN features in the spectra of “rebrightenings” during GRB afterglow decay, at intermediate redshifts,

most recently GRB 130427A at $z = 0.34$ (Melandri et al. 2013; Maselli et al. 2013), up to $z \simeq 1$ (Della Valle et al. 2003); *iii*) the host galaxies are spiral and irregular with active star formation (Fruchter et al. 2004) typical for environments hosting core-collapse SNe (CC-SNe; Kelly et al. (2008); Raskin et al. (2008); Modjaz et al. (2011)). If detected, afterglow emissions of SGRBs tend to be very weak compared to those of LGRBs, consistent with less energy output and pointing to hosts lacking star formation. Weak X-ray afterglow emissions discovered by High Energy Transient Explorer-2 (HETE II) in GRB 05059B and *Swift* in GRB 050507 (Berger 2006) were anticipated for GRBs from rotating black holes (van Putten & Ostriker 2001).

Swift has been key to the discovery of a diversity beyond the BATSE classification. GRB 060614 ($T_{90} = 102$ s) has no detectable supernova (Della Valle et al. 2006; Fynbo et al.

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2006; Gal-Yam et al. 2006) and GRB 050724 is a SGRB with Extended Emission (SGRBEE) with $T_{90} = 69$ s in an elliptical host galaxy (Berger et al. 2005c; Berthelmy et al. 2007), neither which is readily associated with a massive star. Since then, the list SGRBEEs has grown considerably.

A primary question is whether the observed z -distribution of SGRBs is genuinely different from that of LGRBs. If SGRBs are relatively nearby, as suggested by the currently available redshift data (Coward et al. 2013; Sieliez et al. 2014), here shown in Table 1, they may originate delayed to the cosmic star formation rate. In particular, a binary origin can account for an apparent offset in mean redshift of order unity (Portegies Zwart & Yungelson 1998; Guetta & Piran 2005). Though highly plausible (Narayan et al. 2001; Fox et al. 2006), direct evidence for an origin of SGRBs in mergers is relatively weak compared to the evidence for a major fraction of LGRBs originating in CC-SNe. In essence, this fact points to an intrinsic faintness of candidate progenitors.

Here, we set out to rigorously determine whether the observed redshift distributions of SGRBs and LGRBs are distinct. To circumvent the limitation of small sample sizes in a model independent approach, we apply a Monte Carlo (MC) simulation to the extraction of samples of size 15 (for SGRBs), 7 (for SGRBEEs) and 3 (for low- z LGRBs with no supernova, LGRBNs) from the z -distribution of LGRBs. It obtains probabilities for mean redshifts to occur by chance with equivalent levels of confidence for SGRBs, SGRBEEs and LGRBNs to be distinct from LGRBs.

2 MC ANALYSIS

Table 1 lists *Swift* events of SGRB, SGRBEE and LGRBNs with redshifts (Fig. 1) and, when available, hosts and location in the $E_{p,i} - E_{iso}$ plane. Note that GRB 060614 is listed both as a SGRBEE and LGRBN. The peak energy $E_{p,i}$ is the photon energy at which the νF_ν spectrum in the cosmological rest-frame peaks; it typically ranges from tens of keV to several hundreds of keV. E_{iso} is the isotropic-equivalent energy radiated by a GRB during its whole duration assuming spherically symmetric emission. E_{iso} is used due to the still lacking reliable information on the degree of collimation in the individual GRB events. In the $E_{p,i} - E_{iso}$ plane, long GRBs follow the *Amati-correlation* (Amati et al. 2002, 2006).

In Fig. 2, both SGRBEE and LGRBN show a first spike inconsistent with the Amati-correlation for normal LGRBs and a long soft tail consistent with it, notably GRB 050724 (Berthelmy et al. 2005; Amati et al. 2010), GRB060505 (Thone et al. 2008; Ofek et al. 2007), GRB060614 (Mangano et al. 2014; Caito et al. 2009), see further Xu et al. (2009), GRB060218 (Amati et al. 2007), GRB071227 (Caito et al. 2010) and GRB061021 (Golenetskii 2006). This sample is key to a new diversity in GRBs, beyond the BATSE classification of SGRBs and LGRBs.

The mean values μ of the observed redshifts, i.e., μ_S^N of LGRBNs, μ_{EE}^N of SGRBEEs, μ_S of SGRBs and μ_L of LGRBs, satisfy

$$\mu_S^N < \mu_{EE} < \mu_S < \mu_L, \quad (1)$$

where $\mu_S^{EE} = 0.5286$, $\mu_S = 0.8587$, $\mu_L^N = 0.1870$, and $\mu_L = 2.1069$.

We now consider the probability that, by mean redshift, our samples of SGRBEE ($n_1 = 7$), SGRB ($n_2 = 15$) and LGRBNs ($n_3 = 3$) are drawn from the observed distribution of LGRBs ($n = 230$). Because of the small n samples and the broad distribution of redshifts of LGRBs (with an observational bias towards low z), we proceed with an MC test by drawing samples of size n_i ($i = 1, 2, 3$) from the distribution of the $n = 230$ redshifts of the latter. Doing so N times for large N , we obtain distributions of averages m_i of the redshifts in these small n samples under the Bayesian null-hypothesis of coming from the distribution of redshifts of LGRBs. Fig. 2 shows the results for MC with 10^6 realizations. A comparison with such MC test on a Gaussian distribution with mean \bar{z}_L and standard deviation $\sigma_L = 1.3459$ of LGRBs is included for reference. The results clearly demonstrate the need for a Monte Carlo simulation on the observed distribution of redshifts of LGRBs for an accurate estimate of confidence levels, especially when departures from \bar{z}_L are substantial. Based on (1), the MC analysis shows

$$\begin{aligned} \text{SGRBEE} \not\subset \text{LGRB} &: \sigma = 4.6700 \\ \text{SGRB} \not\subset \text{LGRB} &: \sigma = 4.7530 \\ \text{LGRBN} \not\subset \text{LGRB} &: \sigma \simeq 4.3140 \end{aligned} \quad (2)$$

Relative to normal LGRBs, the distinct morphology of SGRBEE and LGRBNs in Fig. 2 and redshifts (2) provides evidence that SGRBEE and LGRBN belong to the same class of events and likely originate in mergers as do classical SGRBs. A technically long duration EE to a merger explains LGRBNs, i.e., LGRBs without association with an SN. This interpretation is further supported by the elliptical host galaxies of SGRB 050509B and GRBEE 050724, which sets these events rigorously apart from massive star progenitors to normal LGRBs.

Our MC results (2) also show that our sample of SGRB(EE)s has negligible contamination by short duration events derived from LGRBs with durations $T_{90} \lesssim 20$ s, that may be present at redshifts $z > 1$ (Bromberg et al. 2013). The time scale of 20 s derives from a 10 s time-scale of shock break-out in CC-SNe identified in a detailed matched filtering analysis of the 1491 LGRBs in the BATSE catalogue (van Putten 2012). Furthermore, the soft tails of both SGRBEE and LGRBN show a location in the $E_{p,i} - E_{iso}$ plane consistent with that of LGRBs associated with a SN and, more generally, with the Amati-correlation for normal LGRBs, that are all expected to be associated with a SN by the correlation of their redshift distribution to the cosmic star formation rate. E_{iso} of the two SGRBEEs highlighted in Fig. 2 (GRB 071227 and GRB 050724) fall within the range of the E_{iso} 's of normal LGRBs with SNe and, in fact, are at the lower end of the E_{iso} of the SGRBEEs listed in Table 1. SGRBEE and LGRBs should hereby have essentially the same observational selection effects. On this basis, (2) shows GRBEEs and LGRBs to be distinct populations at a level of confidence exceeding 4σ .

3 MERGERS AND EXTENDED EMISSION

A merger origin of SGRBs and SGRBEEs naturally accounts for a delay in redshift relative to the cosmic star formation

Table 1. *Swift* detections of SGRB, SGRBEE^a and LGRBNs sorted by redshift.

		T_{90}	z	Host ^b	E_{iso}^c (10^{52} erg)	E_p^c (keV)
SGRB	061201	0.760	0.111	galaxy cluster [1]	0.013	969
	050509B	0.073	0.225	elliptical galaxy [2]	0.00027 ± 0.0001 [3]	-
	060502B	0.131	0.287	massive red galaxy [4]	0.022	193
	130603B	0.18	0.356	SFR [5]	0.21 ± 0.02 [6]	90 [6]
	070724A	0.4	0.457	moderate SF galaxy [7]	-	-
	051221A	1.400	0.547	SF, late type galaxy [8]	0.25 [9]	-
	131004A	1.54	0.717	low mass galaxy [10]	-	-
	101219A	0.6	0.718	faint object [11]	0.48	842
	061217	0.210	0.827	faint galaxy [12]	0.008 [12]	-
	090510	0.3	0.903	field galaxy [13]	3.8 [13]	-
	070429B	0.47	0.904	star forming $\simeq 1.1 M_{\odot} \text{ yr}^{-1}$ [14]	-	-
	060801	0.49	1.131	-	0.027 [15]	-
	100724A	1.4	1.288	probably LGRB [16]	-	-
	050813	0.45	1.8	galaxy cluster [17,18]	0.017 [18]	-
	090426	1.2	2.609	irregular SF galaxy [19]	-	-
SGRBEE	060614 ^{d e f g}	108.7	0.125	faint SFR [20,21]	0.21 ± 0.09 [20]	55 [20]
	050724 ^{d e f g}	69	0.258	elliptical, weak spiral [22]	0.0099 [23]	-
	071227A ^{e f}	1.8	0.384	edge-on spiral [24]	0.008 [25]	-
	061210 ^{d e f g}	85.3	0.41	bulge dominated [26]	0.046 [26]	-
	061006 ^{d e f g}	129.9	0.438	exponential disc profile [27]	0.18	955
	070714B ^{d e f g}	64	0.92	moderately SF galaxy [28]	0.16 [28,29]	-
	050911 ^{d e}	16.2	1.165	EDCC493 cluster [30]	0.0019 [30]	-
LGRBN	060505	4	0.089	spiral, ionized H, no SN [31]	0.0012 [21] - 0.0039	120
	060614 ^{d e f g}	108.7	0.125	faint SFR, no SN [20]	0.21 ± 0.09 [21]	-
	061021	46	0.3462	no SN [32]	0.68	630

^a From HEASARC (2014); ^b galaxy type, SN association; ^c Isotropic-equivalent energy and peak energy for events with reliable estimates of the bolometric E_{iso} across a large enough energy band, under the assumption $\Omega_m = 0.3$ and a Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$; ^d (Perley et al. 2009); ^e (Norris et al. 2012); ^f (Coward et al. 2012); ^g (Gompertz 2014); [1] Berger et al. (2007d); [2] Fong et al. (2010); Page et al. (2006); Perley et al. (2009); [3] Bloom et al. (2006, 2007); [4] Bloom et al. (2007); [5] Cucchiara et al. (2013); [6] Frederiks et al. (2013); [7] Kocevski et al. (2012); [8] Berger & Soderberg (2005); Berger et al. (2007a); [9] Golenetskii (2005); [10] Perley et al. (2013); [11] Perley et al. (2010); [12] Berger et al. (2006); de Ugarte Postigo et al. (2006); [13] Rau et al. (2009); Nicuesa Guelbenzu et al. (2012); [14] Cenko et al. (2008); [15] Cucchiara et al. (2006); Berger et al. (2007b); [16] Ukwatta et al. (2010); [17] Bloom et al. (2007); Prochaska et al. (2006); Berger (2006); Ferrero et al. (2007); [18] Berger (2005b); [19] Antonelli et al. (2009); [20] Amati et al. (2008); [21] Fynbo et al. (2006); Cobb et al. (2006); [22] Berger et al. (2005c); Page et al. (2006); Berger et al. (2007b); Fong et al. (2010); [23] Prochaska et al. (2005); [24] Berger et al. (2007c); [25] Berger et al. (2007e); [26] Cenko et al. (2006); [27] Fong et al. (2010); Berger et al. (2007b); [28] Graham et al. (2009); [29] Graham et al. (2007); [30] Berger et al. (2007a); [31] Jakobsson & Fynbo (2007); [32] Moretti et al. (2006)

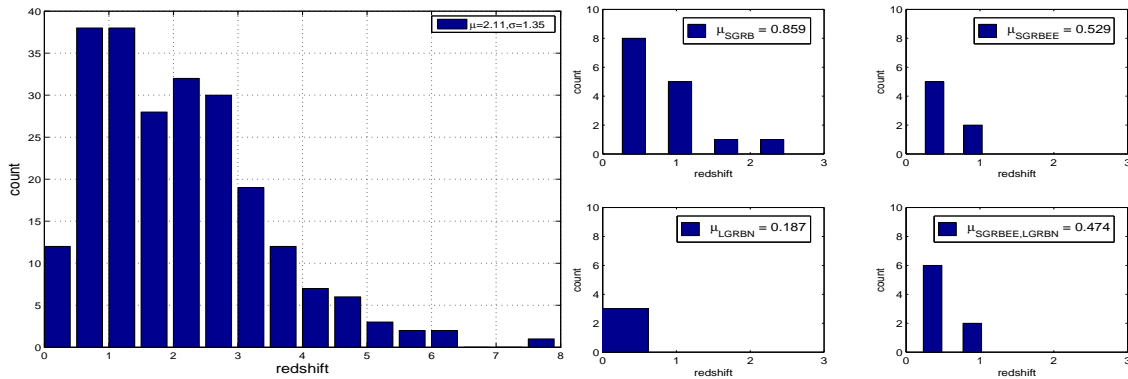


Figure 1. (Left:) the redshifts of 230 LGRBNs in the *Swift* catalogue shows a mean redshift $\mu = 2.11$ with standard deviation $\sigma = 1.35$. This distribution is significantly biased to towards low redshifts. (Right:) same for SGRB, SGRBEE, LGRBN and SGRBEE+LGRBNs.

rate and a dissociation to host galaxy type. Mergers of interest are NS-NS and NS-BH coalescence, producing stellar black holes with an accretion disc or torus (BHS) in common with core-collapse of high mass stars (more massive than those producing neutron stars).

A BHS may produce a long-lived inner engine in angular momentum loss from rapidly rotating black holes, as opposed to short-lived activity from hyper-accretion onto a slowly spinning black hole following tidal break-up of a PNS (van Putten & Ostriker 2001). In particular, high reso-

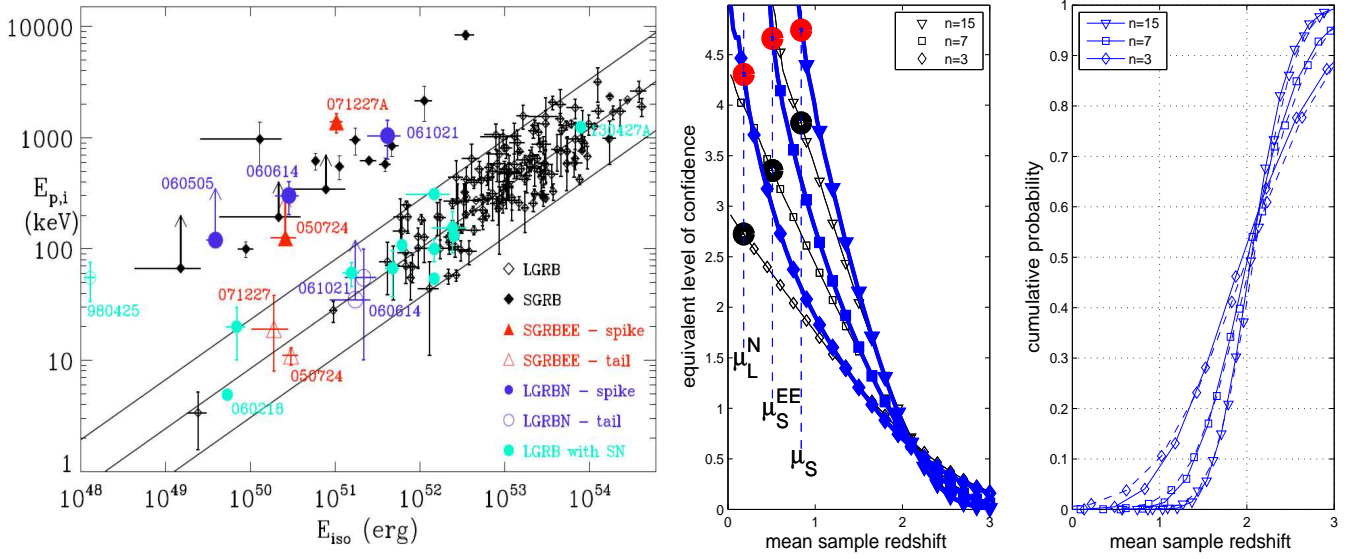


Figure 2. (Left:) shown are SGRBEE and LGRB(N)’s in the $E_{p,i} - E_{iso}$ plane (Amati et al. 2002, 2006), including GRB-SNe 030329, 050525A, 081007, 091127, 100316D, 101219B. The lines are the best-fit of the $E_{p,i} - E_{iso}$ correlation for normal LGRBs and its $\pm 2\sigma$ confidence region. The sub-energetic GRB980425/SN1998bw has a distinguished symbol. Highlighted are GRBEEs 050724 and 060614 (also a LGRBN). The tail of these two SGRBEEs (open triangles, red) and that of the more luminous counterparts listed in Table 1 falls well within those of LGRB with SNe indicated by medium sized filled circles (green). In contrast, the initial pulse of SGRBEEs (solid triangles, red) falls into the separate group of SGRBs, in common with the initial pulse of LGRBNs (large size filled circle, blue). Limits shown are 90% confidence levels. Data mostly from (Amati et al. 2008, 2009; Cano et al. 2014; Swift/BAT 2014). (Right two panels:) an MC simulation produces probabilities $P_i(\mu < z)$ as a function of z in the three samples of size $n_i = 15, 7, 3$ extracted, respectively, from the redshift distribution of LGRBs (blue curves). For comparison, the same is shown using a Gaussian distribution with $\sigma_L = 1.35$ for the latter (black curves). In the Bayesian interpretation, $P_i(\mu < z)$ are probabilities of observing averages $\mu < z$ under the null-hypothesis of a redshift distribution given by that of LGRBs. Being small, we convert $P_i(\mu < z)$ ’s to equivalent confidence levels for the null-hypothesis to be false, i.e., for the three small samples to be drawn from a redshift distribution different from that of LGRBs. Vertical dashed lines show the μ_L in (1) and their intersections with the MC results (red and black dots). Also shown are the cumulative distributions of the distributions of mean redshifts of the samples of size $n_i = 15, 7, 3$ extracted from the redshifts of LGRBs (continuous lines), including that of a Gaussian distribution (dashed lines) with the same mean and standard deviation shown in Fig. 1.

lution numerical simulations show NS-NS producing rapidly rotating black holes (Baiotti et al. 2008), while NS-BH binaries are expected to be diverse harbouring slowly to rapidly spinning black holes. Accordingly, we identify SGRBEE and LGRBNs with mergers involving the latter.

Since the soft tail of SGRBEEs and LGRBs feature share the same Amati-correlation, they likely share the same inner engine, i.e., rapidly rotating black holes, not PNS. (If produced in mergers, PNS are short-lived with no bearing on extended emission.) This safely accounts for the most hyper-energetic GRB-SNe, whose output exceeds the maximal spin energy $E_c \simeq 3 \times 10^{52}$ erg of a PNS with a mass of $M = 1.45M_\odot$ and radius $R = 12$ km to be compared with the maximal spin energy $E_{rot} = 6 \times 10^{54}$ erg of a Kerr black hole of mass $M = 10M_\odot$ (van Putten et al. 2011).

4 DISCUSSION

The *Swift* discovery of SGRBEEs, e.g., GRB 060724, and LGRBNs, e.g., GRB 060614, highlights a new diversity in LGRBs with no apparent association with massive stars.

Based on an MC analysis, the observed redshift distributions of SGRB and SGRBEEs are distinct from that of LGRBs at 4.75σ and 4.67σ , respectively. Further supported by their distinct morphology in the $E_{p,i} - E_{iso}$ plane and

hosts that include elliptical galaxies, this points to a common origin in mergers of both, i.e., of the NS-NS and NS-BH variety with long-lived and short-lived inner engines, respectively.

In a common origin of SGRBEEs and LGRBNs, we identify the initial pulse with the “switch on” of SGRBEEs in binary coalescence similar as in classical SGRBs (see also Ghirlanda et al. (2011)) and the extended emission with a rotating black hole, rather than a PNS, slowly losing angular momentum.

The fact that the soft tail of SGRBEE and LGRBNs follows the Amati-correlation holding for normal LGRBs points to a common long-lived inner engine which is a rotating black hole to all three groups. This is consistent with (a) the absence of any signature of PNS formation in a high-frequency analysis of *BeppoSAX* light curves (van Putten et al. 2014) and (b) evidence for black hole spindown observed in normalized light curves in the BATSE catalogue (van Putten 2012). Apart from the low number counts, the only reservation would be extremely subluminal CC-SNe (cf. Pastorello et al. (2007)), that would be undetectable in our sample LGRBNs.

Following Guetta & Della Valle (2007), local rates of GRB-SNe and LGRBNs can be estimated from the observed events taking into account finite angular and temporal sky coverage and sensitivity distance. With no correction for

beaming, we find, respectively, the event rates $1.13^{+1.98}_{-0.85}$ (cf. Guetta et al. (2011)) and $0.053^{+0.10}_{-0.036}$ Gpc $^{-3}$ yr $^{-1}$. It shows a ratio of LGRBN to GRB-SN of about 5%, and likely no larger than about 30%.

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